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FINAL REPORT

Contract #: N00014-91-C-0226

R&T Code: s400058fel04

PRINCIPAL INVESTIGATOR: Dr. John M. J. Madey

INSTITUTION: Duke University, FEL Laboratory

GRANT TITLE: "A Center for Medical and Materials Science Research with Free Electron Lasers"

REPORTING PERIOD: April 1, 1991 - December 1, 1994

AWARD PERIOD: April 1, 1991 - June 30, 1994

OBJECTIVE: The objective of the present program is to develop an integrated laboratory dedicated to the exploration of the medical applications and materials of free-electron lasers with the capability to:

- a. develop and apply advanced FEL and medical technologies and techniques;
- b. provide user facilities to qualified unaffiliated researchers through and applications program; and
- c. carry out an ongoing, high level critical review of the current and possible future applications of FELs in medicine.

APPROACH: The Duke Center has offered free operating time, technical support, and limited financial support for qualified researchers with an interest in the use of the Center's FEL light source technology. Proposals for use of the facility are reviewed by a peer review panel on the basis of scientific merit, without regard to institutional affiliation. We will continue this element of the program in the proposed research with two modifications: (1) the addition of two postdoctoral fellows to serve as mentors to new researchers unfamiliar with the resources and operational capabilities of the Center, and (2) access to the Center's new short wavelength FEL and synchrotron radiation light sources.

The FEL research and development work carried out by the faculty and staff of the Center will also be continued. With the commissioning and routine operation of the Center's Mark III infrared FEL system, this effort will focus primarily on the implementation of incremental upgrades to the Mark III system and to the integration, commissioning and operation of the Center's ultraviolet and x-ray FEL devices. This effort will benefit substantially from the establishment by Duke of two new junior faculty appointments in FEL physics and by the growing scientific exchange between the Center and the Budker Institute of Nuclear Physics in Novosibirsk, the FSU's principle FEL R&D laboratory.

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The three new proposed research thrusts, in surgery, imaging and photobiology, will be conducted primarily by Center-affiliated researchers to insure an effective long-term, coordinated effort. In these thrusts, we will undertake a range of complementary research efforts in which FEL technology is applied both to advance the fundamental objectives of current research in these fields and to explore a representative sample of the potential clinical and diagnostic applications.

ACCOMPLISHMENTS: The ongoing users program has been supplemented with these additions of two postdoctoral fellows who will serve as mentors and coordinators for investigators who need assistance in planning and executing their experiments. It is almost always necessary to have someone from the FEL scientific staff to be present and usually assist during experiments done by outside investigators. Mark III beam-time is now approximately 2000 hours/year and expanding.

In anticipation of soft x-ray radiation from the NIST undulator, the OK-4 wiggler at VUV and soft-x-ray region and hard x-rays from the inverse Compton scattering mm wave FEL, beamline planning and design has begun.

The finding that the OK-4 wiggler VUV FEL can produce tunable, extremely bright gamma radiation from 1-250 MeV, has gotten the attention of the nuclear physics community. Such a source may provide unprecedented capabilities for spectroscopy of nuclear energy levels. A two-day workshop with nuclear physicists from throughout the world in attendance will be held December 13-14, 1994, at Duke to explore the applications of our gamma beam. The workshop deliberations should give us guidance on beamline design for gamma photons.

During the past year experimental work continued on infrared two-photon spectroscopy of organic semiconductors and on porphyrins in solutions by investigators from the University of Utah. Work was initiated on non-linear effects at surfaces in the IR by investigators from UNC, Duke and University of Wisconsin.

Mode-selective chemistry at surfaces and in gas phase is a very important area for both outside users and FEL investigators. A mass spectrometer capable of detecting such laser-induced reactions has been constructed and is ready for testing and use.

Outside investigators from UNC and investigators from FEL staff have succeeded in producing narrow-line spectra of acetylene in gas phase in the C-H stretch region. This demonstration gives the IR FEL true high-resolution spectroscopic capabilities through use of phase and mode-locking in the cavity optical path as developed and described by Szarmes.

In accordance with our initial approach, we have constructed and commissioned 11 sections of our linear accelerator. Driven by three S-band klystrons, this accelerator has produced a 250 MeV electron beam at 1 μ -sec pulse duration, 2 Hz operation with 20 millamps peak current. The storage ring has been completed, was placed under

vacuum and, on November 4, 1994, at approximately 1:30 AM, the electron beam from the linear accelerator was injected into the ring and achieved a complete orbit. Radiation safety surveys, shielding adjustments and personnel protection interlock testing are under way at this writing. On November 11, 1994, stored beam in the ring was achieved. The lifetime of the stored beam was more than 2 hours.

A new electron gun has been constructed and installed on the Mark III. This new gun should give lower emittance and better electron beam quality than in the past. In turn the intensity and stability of the optical pulse from the Mark III will be improved.

Two new faculty, Dr. V. Litvinenko and Dr. P. O'Shea have been added to the permanent staff at the Duke FEL Laboratory, with chief responsibilities for storage ring and linear acceleration, respectively.

We have completed our initial studies on electron beam structures in phase space and have demonstrated that tomography can be done on the electron beamline in the Mark III, giving a good representation of the beam in phase space. We have also completed initial work on out-coupling of IR radiation through a central hole in one of the cavity mirrors of the Mark III. Out-coupled power can be up to 10% with TEM 00 predominantly. Hole coupling is important for several applications of the FEL including Inverse Compton scattering from the mm wave FEL in the storage ring.

Characterization of the NIST undulator has begun in anticipation of using it as an intense source of 40 Å photons for x-ray microscopy, holography and real-time tomography.

The OK-4 electromagnetic wiggler from BINP in Novosibirsk, Russia, has been purchased and will be transported, calibrated and installed in the spring of 1995. It will serve as the photon source for our FEL which will provide coherent diffraction limited tunable radiation between 4000 Å and 300 Å.

Our new research thrusts in surgery have been initiated with demonstration of low collateral damage incisions by the Mark III IR FEL. Careful control wavelength of average power delivery can give efficient cutting at 3 μ in cornea, brain and spinal cord, peripheral nerve, teeth and skin. The cutting action of the 3 μ FEL pulses seems to be mediated by the very high energy absorption of water which causes cutting by non-linear processes and not by linear (thermal) effects. In the presence of a thin film of water, the enamel of teeth can be cut without heating the pulp tissues, the cornea can be cut without wrinkling due to thermal processes, peripheral nerves can be sectioned without severe damage, and brain tissue can be cut with only a few microns of damage at the edges of the incision. With the capability of pulse-length shortening to 200 fsec (from the present 1.8 psec) and phase-locking of the pulses, cutting efficiency and low collateral damage may even be further improved. Functional studies on healing and surgical results are underway. Wavelength-specific effects, especially at 3.4 μ (C-H stretch frequency) and 6.0 at 6.45 (amide stretch frequencies), are of high priority.

The fiber-optics delivery of IR FEL light is of very great importance in many surgical applications. We have tested delivery of high peak pulsed IR power through a number of fiber optics of different compositions. In the IR to about $4\text{ }\mu$, sapphire is very promising. Also the hollow quartz waveguide gives reasonable transmission with wide wavelength range at high power; however, a number of fiber optic zirconium based glasses and chalcogenide-based glasses cannot transmit high-power IR pulses without damage. Suitable fiber optic for the critical wavelength of $6.45\text{ }\mu$ are being tested.

The physiologic responses of cell suspensions to the impact of high peak pulsed power IR at $3.0\text{ }\mu$ has been initiated and is the subject of independent report to ONR.

Multiphoton processes in simple molecules - such as water - up to very complex molecules - such as porphyrins and proteins - are under very active investigation. Preliminary results indicate that the liquid water does not make any detectable hydroxy radicate even at power densities of more than 1 GW/cm^2 . Gaseous H_2O , however, is known to generate hydroxy radicate very easily. There is good indication that multiphoton ionization does occur at the C-H stretch frequency in porphyrins in CCl_4 solutions.

The new, high peak power, tunable sources from the storage ring operations have attracted a number of users and that number will certainly grow. We have initiated discussions with Dr. L. Beese, Dr. S. White and Dr. D. Richardsen (Duke), concerning the beamline and end requirements for high resolution x-ray crystallography on small crystals using the multi-wavelength anomalous dispersion (MAD) technique. Low angle x-ray scattering requirements for biological materials and polymers have been discussed with Dr. M. Reedy (Duke). Design and planning for the NIST undulator radiation at 4 nm as the source for high-contrast x-ray microscopy and holography of living cells is part of the Ph. D. work of Lewis Johnson, (4th year graduate student in physics, Duke). The potential of x-ray, real-time tomography on small (sub-millimeter) objects is under discussion with Dr. A. Johnson (Duke).

In addition to active discussions concerning the use of the bright gamma source in nuclear physics applications at our recent workshop, we have had discussions with Dr. K. Weeks (Duke) concerning the use of tunable gammas in treatment of tumors.

A growing collaboration with Dr. H. Ade (NCSU) is centered around the use of the very high peaked pulse power, tunable FEL VUV/soft x-ray source of the OK-4 wiggler in photoelectron imaging.

We have also had discussions with Dr. G. Kulipanov and Prof. A. Skrinsky, Budker Institute of Nuclear Physics, and Prof. Y. Molin and A. Petrov of the Institute of Chemical Dynamics in Novosibirsk, Russia, concerning the separation of stable isotopes by using infrared FEL's. We hope to perform preliminary experiments at Duke in collaboration with our Russian colleagues in 1995. In addition, we have begun a discussion with Dr. H. Robitz (Princeton) concerning the use of the IR FEL for mode-selective chemistry.

Discussions are under way to extend the surgical use of the Mark III to direct endocardial reperfusion in experimental animals (Dr. R. Anderson and D. Sabiston, Duke). Non-survival experiments may be initiated in 1995.

The use of synchronized light from the storage ring sources and the Mark III infra-red FEL in pump-probe experiments is of high priority. Dr. R. Palmer and Dr. R. MacPhail (Duke) are designing a picosecond FTIR using the white synchrotron radiation as a source to probe the mid IR spectrum of molecules excited (pumped) by the Mark III FEL. A large number of experiments using this synchronized pump-probe capability between the ring and Mark III are anticipated including experiments throughout the ultraviolet, soft x-ray and hard x-ray regions.

Because of the great experimental demand for the Duke FEL light sources, we have asked for and received permission from the University to seek funding from foundations and other sources for a 24,000 sq. ft. to the Duke FEL laboratory. This addition will be composed of two sections. The first will be a 20 foot wide expansion of our ring room along the entire North wall (300 feet). The addition will have a mezzanine area and will allow ample room for experimental areas and shop areas. The second section will be an addition of a two story experimental area at the East end of the ring room. This area will have space for complete operating room, gamma experimental gallery and stable infrared optical area as well as additional offices in the front of the building.

Maximum operational times of the ring sources and the Mark III are of great importance. The Mark III and the ring are independent units and can be operated separately, except when tunnel access is required. The ring can operate with the tunnel opened but the Mark III cannot. With this exception, which should cause little difficulty, we can anticipate operating time (actual photon beam time) of 2000-3000 hrs./yr. on the Mark III. The ring will also likely approach 3000 hrs./yr. of circulating beam time. Since the ring can support more than one user at a time, we anticipate approximately 4500 user hrs./yr. on the ring sources when the ring and beamlines are fully operational.

We have been able to operate the Mark III 24 hr./day, 5 days/week in the summer of 1994 and find it is much better for the users and the operators to run continuously. This avoids the uncertainty of when the photon beam will be available after start-up of the system.

Duke FEL 1993-1994 Refereed Publications

1. G. A. Barnett, "Hole-Coupled Free Electron Lasers: A Transverse Mode Analysis." Dissertation submitted to the Department of Physics, Duke University, for the degree of Doctor of Philosophy, 1994.
2. G. A. Barnett, Stephen V. Benson, and John M. J. Madey, "Warm Cavity Modes of Free-Electron Laser Resonators with On-Axis Holes." IEEE Journal of Quantum Electronics **29**, 479-486, (1993).
3. G. A. Barnett, S. V. Benson, and J. M. J. Madey, "Laser Resonators and Coherent Optics: Modeling, Technology, and Applications." SPIE 1868, 171-179 (1993).
4. J. A. Hoke, E. J. Burkes, Jr., E. D. Gomes, B. A. Hooper, M. L. Wolbarsht, "The Effect of Free Electron Laser Exposure on Tooth Structure." Lasers in the Life Sciences. (Accepted for publication).
5. Brett A. Hooper, Stephen V. Benson, and John M. J. Madey, "Conversion Efficiency Optimization of Free Electron Laser Light." Nuclear Instruments and Methods in Physics Research **A331**, 93-97 (1993).
6. Brett A. Hooper, Daniel J. Gauthier, and John M. J. Madey, "Fourth-Harmonic Generation in a Single Lithium Niobate Crystal with Cascaded Second-Harmonic Generation." Applied Optics **33**, 6980-6984 (1994).
7. V. N. Litvinenko and N. A. Vinokurov, "On the Classical Analog of the Einstein Relations Between Spontaneous Emission, Induced Emission and Absorption." Nuclear Instruments and Methods in Physics Research **A331**, 440-449 (1993).
8. V. N. Litvinenko, "3D Free Electron Laser Gain for an Electron Beam with Finite Emittance and Energy Spread." Nuclear Instruments and Methods A. (Accepted for Publication.)
9. V. N. Litvinenko, "Giant Laser Pulses in the Duke Storage Ring UV FEL." Nuclear Instruments and Methods A. (Accepted for Publication.)
10. Vladimir N. Litvinenko, John M. J. Madey and Nikolay A. Vinokurov, "Component Technologies for a Recirculating Linac Free-Electron Laser." SPIE **2121**, 21-37 (1994).
11. Chad B. McKee, "Creation, Transport and Measurement of Bright Relativistic Electron Beams," Dissertation submitted to the Department of Physics, Duke University, for the degree of Doctor of Philosophy, August, 1994.

17. C. B. McKee, and John M. J. Madey, "Electron Beam Control Using Experimentally Measured Transport Matrices." *Laser and Particle Beams* **12**, 17-21 (1994).
18. P. G. O'Shea, "High-Brightness RF Photocathode Guns for Single-Pass X-Ray Free Electron Lasers." *Nuclear Instruments and Methods A.* (Accepted for Publication.)
19. E. B. Szarmes, "A Birefringent Beamsplitter for Intracavity Mode Selection in High-Power Multi-Mirror Lasers", *Applied Optics*, **33**, 6953-6964 (1994).
20. E. B. Szarmes and J. M. J. Madey, "Submegahertz Spectral Resolution in a Free-Running Infrared Free-Electron Laser Oscillator." *International Quantum Electronics Conference*. OSA Technical Digest Series **9**, 241-242 (1994).
21. E. B. Szarmes and J. M. J. Madey, "High Resolution Infrared Spectroscopy on the Mark III Free-Electron Laser." *Proceedings of the IEEE Lasers and Electro-Optics Society (LEOS '93)*, 728-729 (1993).
22. Eric B. Szarmes and John M. J. Madey, "The Michelson Resonator Free-Electron Laser, Part I: Passive Mode Structure and Mode Decay." *IEEE Journal of Quantum Electronics*, **29**, 452-464 (1993).
23. Eric B. Szarmes and John M. J. Madey, "The Michelson Resonator Free-Electron Laser, Part II: Supermode Structure and Mirror Detuning Effects." *IEEE Journal of Quantum Electronics*, **29**, 465-478 (1993).
24. Eric B. Szarmes, Angus D. Madden and John M. J. Madey, "Observation and Characterization of Frequency-Chirped Optical Pulses on the Mark III Free Electron Laser." *Nuclear Instruments and Methods A.* (Accepted for Publication.)
25. Ying Wu, Vladimir N. Litvinenko and John M. J. Madey, "Study of Undulator Influence on the Dynamic Aperture for the Duke FEL Storage Ring." *Nuclear Instruments and Methods in Physics Research A* **341**, 363-366 (1994).
26. Ying Wu, Vladimir N. Litvinenko, Etienne Forest and John M. J. Madey, "Dynamic Aperture Study for the Duke FEL Storage Ring." *Nuclear Instruments and Methods in Physics Research A* **331**, 287-292 (1993).

The refereed publications for the FEL Conference 1994 are not included in this list.